ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 108-S66

Vibration Characteristics of Concrete-Steel Composite Floor Structures

by Sandun De Silva and David P. Thambiratnam

This paper discusses the vibration characteristics of a concrete-steel composite multi-panel floor structure; the use of these structures is becoming more common. These structures have many desirable properties but are prone to excessive and complex vibration, which is not currently well understood. Existing design codes and practice guides provide generic advice or simple techniques that cannot address the complex vibration in these types of low-frequency structures. The results of this study show the potential for an adverse dynamic response from higher and multi-modal excitation influenced by human-induced pattern loading, structural geometry, and activity frequency. Higher harmonics of the load frequency are able to excite higher modes in the composite floor structure in addition to its fundamental mode. The analytical techniques used in this paper can supplement the current limited code and practice guide provisions for mitigating the impact of human-induced vibrations in these floor structures.

Keywords: concrete-steel composite floor; low frequency; multi-modal; pattern loads; slender structure; vibration.

INTRODUCTION

Background and motivation for present work

New materials technology, aesthetics, planning, and environmental factors have resulted in slender concrete-steel composite floor structures that exhibit complex and excessive vibration. Design codes do not cover such phenomena adequately, whereas practice guides provide simplified techniques that cannot address the complex vibration in these low-frequency structures. There are a number of different configurations of these floor structures, but they are all slender with reduced sections, as they use high-strength materials to achieve longer spans. Figure 1 shows some of the common types, all of which have concrete on a steel deck. These composite floor structures are normally designed using static methods, which will not reveal the true behavior under human-induced loads. Engineers generally limit the slab deflection to a span of 240, but this can increase under dynamic conditions, especially in slender composite floors, such as the one studied in this paper. The one-way spanning behavior of composite floor structures makes them even more vulnerable to vibration problems in contrast to conventional two-way spanning reinforced concrete floor slabs. Reinforced concrete floors will be stiffer and less vulnerable to vibration caused by human-induced loads. In Australia, concrete-steel deck composite floors are used in office buildings, residential apartments, and shopping centers. These floor structures have experienced excessive vibration under human-induced loads and have caused some concerns. The main complaint was the annoying vibration, which was addressed by increasing the damping of the floor panel by using carpets and/or rubber mountings for the exciter or rearranging the fit-out (and hence the pattern loading) of the floor. These retrofits could have been avoided if engineers had investigated the vibration characteristics of the floor at the design stage. In all of these cases, the floor structures seem to respond with the excitation of higher and multi-modal vibration, which occurred even when the load frequency was quite different to the fundamental natural frequency of the floor structure. This type of complex vibration in composite slender floor structures is not currently well understood. This study was motivated by the need to address the knowledge gaps in the complex vibration of slender composite floor structures and the need to provide some design guidance for vibration mitigation. This paper will treat a particular type of concrete-steel deck composite

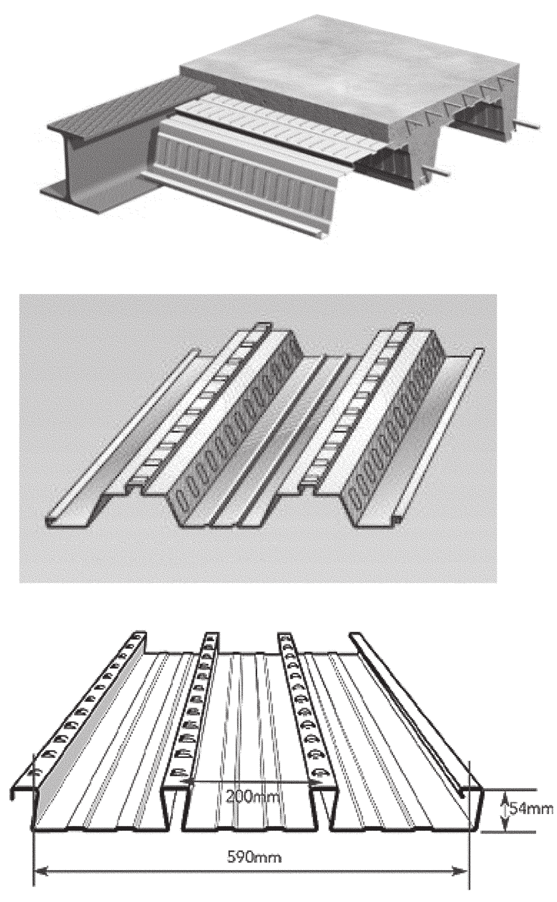

Fig. 1—Composite floors. (Note: 1 mm = 0.04 in.)

ACI Structural Journal, V. 108, No. 6, November-December 2011.
MS No. S-2010-166.R2 received October 13, 2010, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published in the September-October 2012 *ACI Structural Journal* if the discussion is received by May 1, 2012.

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floor structure that has a dovetail profiled steel deck (shown in Fig. 1), although the findings may be applicable to other types (with different deck profiles) with proper consideration of their geometry, stiffness, and applied loads.

Previous work and scope of present work

The structural behavior of concrete-steel deck composite floors subjected to human-induced loads has been investigated by Williams and Waldron,[1] Allen,[2] Da Silva et al.,[3] and El-Dardiry and Ji[4] using finite element (FE) techniques. Some of these research findings have been used in developing the practice guides published by the Steel Construction Institute (SCI)[5]; the American Institute of Steel Construction, Inc. (AISC)[6]; and the International Organization for Standardization.[7] AS3600[8]; AS4100[9]; BS 8110-1:1997[10]; BS 5950-4:1994[11]; and BSI PP 1990:2007[12] for concrete and steel structures provide generic advice, such as isolating the vibration source, providing sufficient damping, or limiting frequencies to control vibration. They do not provide procedures; therefore, designers should use the practice guides[5,6] and the IABSE publication[13] for additional guidance. These practice guides provide acceleration limits for human comfort with respect to frequencies and damping ratios for the design of floor structures under different types of human-induced vibration. Simplified formulae for calculating the fundamental frequency and the acceleration of the floor structure are given. A latter SCI publication[14] also provides some simplified formulae but recommends a lower limit of 3 Hz for the frequency of floor structures. The methods given in the practice guides are approximate, as they are based on simplified structural models that cannot simulate the complex vibration in multi-panel composite floors under pattern loading.

Dynamic loads on a floor system can be due to different human activities, such as dancing (including aerobics and jumping), walking, or running, which apply dynamic loads at different frequencies on the floor, resulting in vibration, increased displacements, and accelerations that can cause discomfort to the occupants. This was studied by Ji and Ellis[15] and Da Silva et al.[3] but mostly pertained to the response of a floor where the activity originated—the activity panel. The response of adjacent panels in a multi-panel floor system has not been explored. This is important in modern buildings with multiple-occupancy floor set-outs in combinations of office/commercial floors and leisure activity halls, such as aerobics halls and gymnasiums in which dance-type activities can take place.

Pattern loading occurs in multi-panel floor systems when different panels are loaded. In modern buildings that have mixed occupancies, office, commercial, and residential areas may be combined with exercise and dance halls, leading to different human-induced loads on the same floor structure. This can result in the multi-modal vibration of the floor structure response, which must be considered in its design. These multi-panel floor systems must therefore be investigated under possible pattern loads applied at different frequencies and the response of both the activity panel and the adjacent (nonactivity) panels must be evaluated. With this in mind, this paper discusses the vibration characteristics of two multi-panel concrete-steel deck composite floor systems (with four and nine panels) subjected to human-induced pattern loadings using FE techniques. Comprehensive load models for dance-type activities are developed and applied as different pattern loads. These load models have variable parameters, such as load intensity, foot contact ratio, activity frequency, and damping. The results show the potential for the adverse dynamic response of these types of floors due to the excitation of higher- and multi-modal vibration under pattern loading. The research findings will enhance the understanding of the vibration response of the composite floor structure and facilitate appropriate provisions for its design. The techniques used in this study can supplement the current limited code and best-practice provisions for mitigating the impact of human-induced vibrations in slender floor structures.

RESEARCH SIGNIFICANCE

Concrete-steel composite floor structures are being increasingly used in multi-story buildings. They have many desirable features but are slender and prone to excessive vibration, which is not currently well understood. The existing design codes and best-practice guides provide generic advice and simple techniques based on the fundamental frequency of the structure and are inadequate to treat the complex vibrations in these structures. This study provides significant insight into the vibration characteristics of these floor structures and confirms the excitation of higher- and multi-modal vibration. The research findings will enable the provision of appropriate measures for mitigating its adverse effects.

PROCEDURE

Description of floor structures

Two multi-panel floor structures are studied in this paper: one with four panels and the other with nine panels. The four-panel flooring system is shown in Fig. 2. It is a 2 x 2 panel model of a 16 x 15.6 m (52.5 x 51.2 ft) floor area with columns in an 8 x 7.8 m (26.3 x 25.6 ft) grid. The primary beams are 530 UB 82 universal beams along the edge parallel to the spanning direction and the secondary beams are 360 UB 45 universal beams simply supported across the primary beams. The columns are the same size as the primary beams. The one-way slab comprised of 150 mm (5.9 in.) thick concrete was laid on a 1 mm (0.04 in.) dovetail profiled steel deck, which is a cast-in-place formwork. The nine-panel flooring system is shown in Fig. 3. The 3 x 3 panel configuration covered a floor area of 24 x 23.4 m (78.7 x 76.8 ft) with 530 UB 82 primary beams and 360 UB 45 secondary beams. The slab thickness is 150 mm (5.9 in.) with a 1 mm (0.04 in.) thick steel deck. The columns are the same size as the primary beams.

FE models

FE models of the four- and nine-panel floors are developed using ABAQUS/Standard Version 6.4[16] for the analytical investigation. The concrete slab is modeled

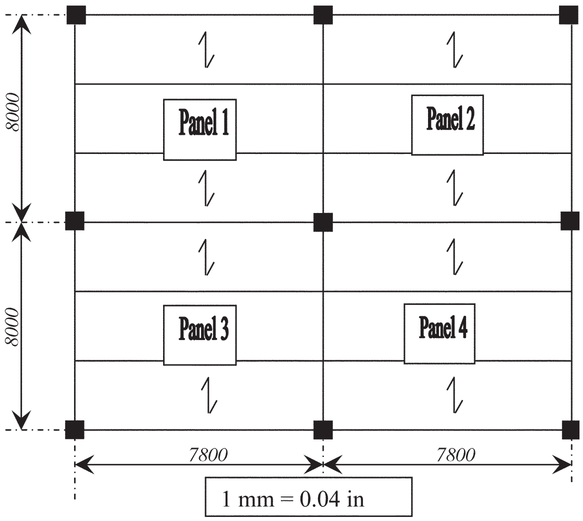


Fig. 2—Configuration of four-panel floor model. (Note: Dimensions in mm.)

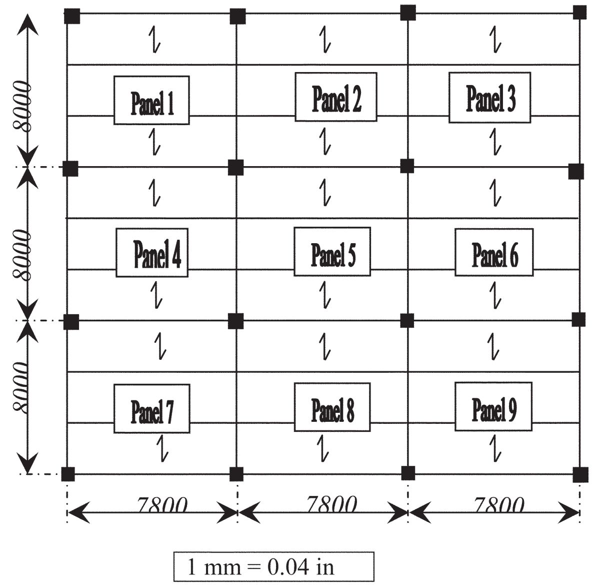


Fig. 3—Configuration of nine-panel floor model. (Note: Dimensions in mm.)

using solid elements, six degrees of freedom (DOF)-Hexagonal Solid 3S6, and the steel deck, including the indentations/ribs, and is modeled using shell elements five DOF-Quadrilateral Shell S4R5, as shown in Fig. 4. Full interaction between the concrete and the deck with no slip between the two materials was assumed by having the same nodes for the two element types at the interface. The primary and secondary steel beams and the steel columns were all modeled using beam elements three DOF-Linear Beam 3B2. The material properties were obtained from tests carried out in the Structures Laboratory at the Queensland University of Technology, according to AS3600.[8] The material properties used in the FE model were a Young's modulus of 205 and 32 GPa (29.7×10^6 and 4.64×10^6 lb/in.^{2}); a Poisson's ratio of 0.3 and 0.2; and a material density of 8000 and 2428 kg/m^3 (499.4 and 151.6 lb/ft^3) for the steel and concrete, respectively. A floor-column model was used in this investigation, as it reduces the additional stiffness provided by either pinned or fixed supports and thus eliminates the false observations, as also done by El-Dardiry and Wahyuni.[17] Necessary boundary conditions were provided to prevent rigid body movements in the floor plane.

The computational techniques used in the modeling and analysis of the concrete-steel deck composite floor are validated by comparing the numerical results of the static, free vibration, and dynamic analysis of a single-floor panel with those from experimental testing. Six floor panels 3.4 m (11.5 ft) long x 1.8 m (5.9 ft) wide x 100 mm (4 in.) thick cast in place on a 1 mm (0.04 in.) dovetailed steel deck were considered. These floor panels were tested under static and dynamic strip loads applied at the midspan and the deflections at the midspan were obtained for validation. Heel-drop tests were also performed on the test panels, and the midspan deflections and accelerations were measured to obtain the natural frequency and structural damping of the floor panel.[18,19]

For FE analysis, a uniform surface pressure across the corresponding elements, in accordance with the experiments, was applied to represent the strip load. Figure 5 shows the static load-deflection plots obtained from the experiments and the FE analysis. The fundamental frequencies of the panel obtained through experimental testing and FE analysis were 14.2 Hz and 14.1 Hz, respectively. In general, the results from the static, free vibration, and dynamic analyses compared well with the experimental results and provided confidence in the techniques presented herein, which were then used in further analysis.[18,19] In addition, the fundamental frequencies of 4.0 Hz and 4.3 Hz for the four- and nine-panel floor structures, respectively, obtained through these techniques agreed reasonably well with the value of 4.28 Hz reported in the manufacturer's literature.[20]

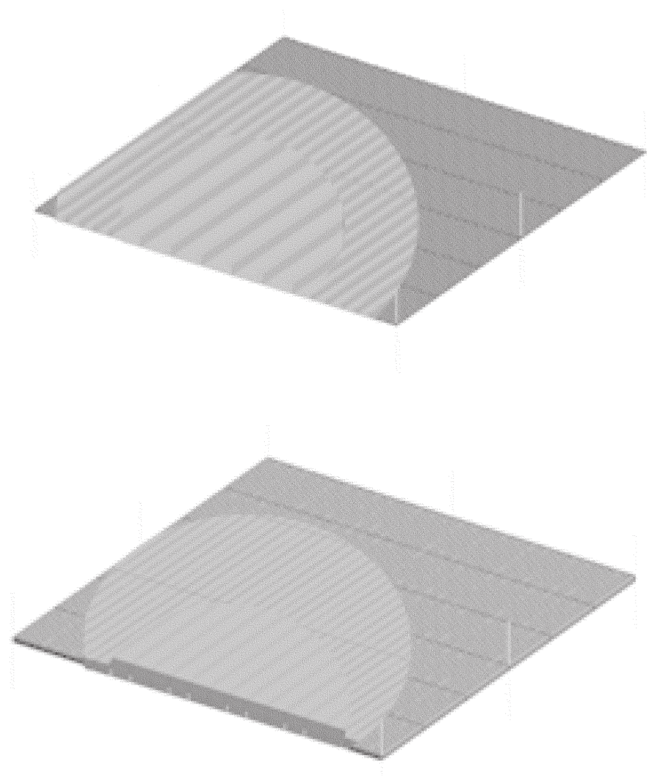


Fig. 4—FE model of floor structure—shell elements for steel deck (T) and solid elements for concrete (B).

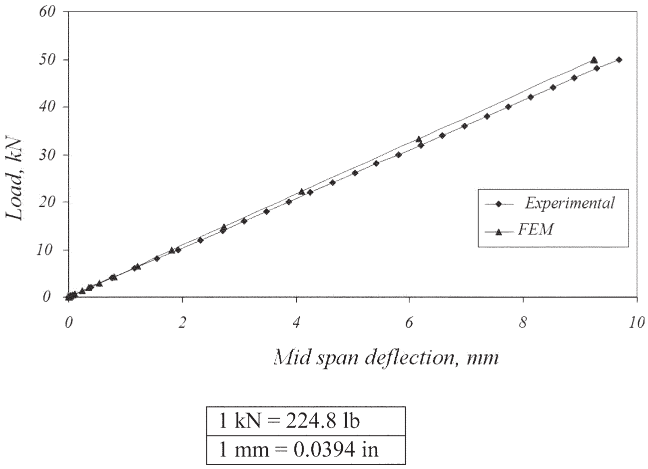


Fig. 5—Load-deflection plots.

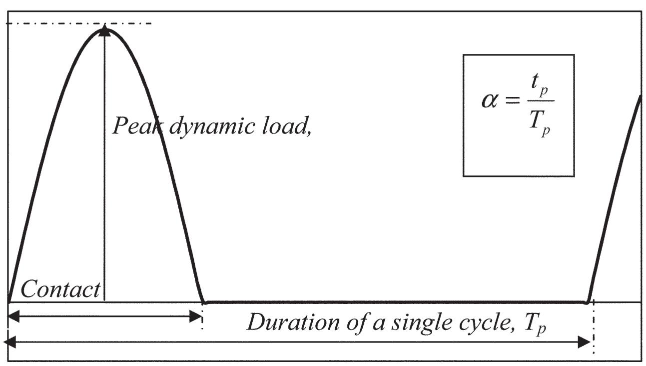


Fig. 6—Graphical representation of dance-type loads.

Human-induced loads

Activities such as walking, running, jumping, and dancing induce vibrational forces on the floor panels. Among these, dance-type activities that are more energetic are more critical, as they usually generate higher dynamic forces; therefore, the vibration response of the composite floor panels under these types of loads is undertaken in this study. Four different dance-type loads defined by their foot contact ratios and at two different load densities are considered. These loads are applied to the FE models of the composite floor and analyzed to obtain the time histories of their acceleration (and displacement) responses. These responses are recorded against four levels of structural damping that can be present in typical floor systems.

The human activity described by dance-type loads produces discontinuous load-time functions, which are similar to running or aerobics. The load-time history of these types of loads can be modeled as a function with two parts: 1) a force function to capture the load applied when the feet are in contact with the structure for a time phase, which is called contact duration; followed by 2) a zero force when the feet are off the floor. The first phase can be described by a half-sinusoidal curve. To represent an entire event of dance-type load activity, a sequence of these half-sinusoidal pluses can be used.[15] Equation (1) presents the mathematical model for this dance-type activity.

$$
\begin{aligned}
F(t) &= (\pi Q/2\alpha)\sin(\pi t/t_p) && 0 \le t \le t_p \\
F(t) &= 0 && t_p \le t \le T_p
\end{aligned}
\tag{1}
$$

where Q is the human load density (weight per unit area); t_p is the contact duration; T_p is the period of the cyclic loading; and $\alpha = t_p/T_p$ is the foot contact ratio. Figure 6 illustrates a graphical representation of the load function. The ratio α of the activity plays a major role in defining the mathematical formulation of dance-type loads (as shown in Eq. (1)) and hence its effect on the floor response. It provides information on how energetic the human activity is. To evaluate the effects of various contact ratios, four different values were used in the current analysis: α = 0.25, 0.33, 0.50, and 0.67. These contact ratios describe the dance-type activities of high-impact jumping, normal jumping, and rhythmic exercise or high- and low-impact aerobics, respectively.[15,19] Two live load intensities—Q = 0.2 and 0.4 kPa (4.2 and 8.4 lb/ft^2)—were used, corresponding to one person per 3.5 and 1.75 m^2 (37.7 and 18.8 ft^2) of floor space, respectively, assuming the average weight of a person to be 70 kg (154 lb). The dead load on the floor slab G was assumed to be 3.5 kPa (73.5 lb/ft^2). These unfactored loads were used to determine the static deflections of the panels under each pattern loading and then used in the dynamic analyses to determine the dynamic amplifications in the deflections and accelerations.[18,19]

Damping

Damping is an important parameter in mitigating excessive vibration in floor structures. A precise value for the damping for a concrete-steel deck composite floor system is, however, mostly unknown.[21] There are a number of damping levels reported in the literature. In general, damping for bare composite floors is reported to be between 1.5 and 1.8%,[21] whereas Wyatt[5] used a damping of 1.5% for a composite steel deck floor. Furthermore, heel-impact tests performed on the tested floor panels revealed damping levels of 1.75 to 2.0% for the bare floor.[19] It should be noted, however, that these damping levels would be rare, as the objects that cause external forces and other standing objects will provide additional damping that would not have been included in this value. For example, the use of partitions on the finished floor system could yield higher damping. Hewitt and Murray[22] used damping of 3% for an office without permanent partitions and damping of 2 to 2.5% for electronic or paperless offices. Even higher damping could also arise in a floor with permanent, drywall partitions—it could be as much as 5 to 6%.[21] Elnimeiri and Iyengar[23] recommended a damping coefficient of 4.5 to 6% for finished floors with partitions, whereas Brownjohn[24] showed that the damping could increase to 10%, depending on the occupant's posture. This would also happen in an environment with an old office floor with cabinets, bookcases, and desks. On the other hand, Sachse[25] proved that the presence of stationary humans could increase the damping of the structure up to 12%. Thus, to observe the responses of the two floor models across a range of credible values of structural damping, this study used four damping levels of 1.6, 3, 6, and 12%. These damping levels depend on the floor's intended use, as described previously,

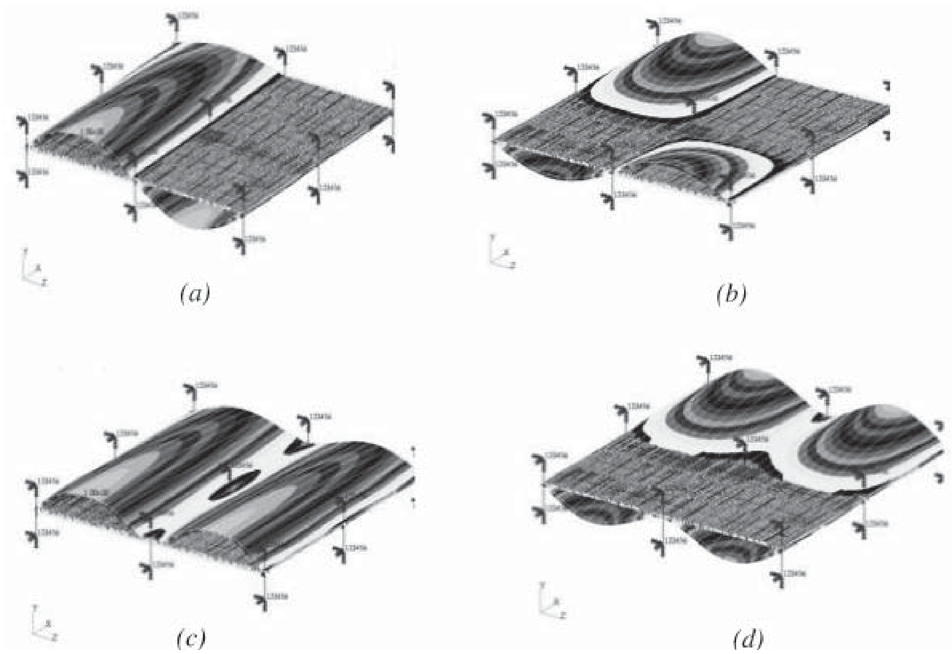


Fig. 7—Mode shapes and natural frequencies of four-panel floor model: (a) first mode at 4.0 Hz; (b) second mode at 5.4 Hz; (c) third mode at 5.9 Hz; and (d) fourth mode at 6.9 Hz.

and were incorporated into the FE models using the explicit damping matrix presented by Clough and Penzien.[26]

Analysis under pattern loads

The response of the four- and nine-panel steel deck composite floors is obtained under different pattern loading cases. The pattern loads used in this paper cover a range of possible loading combinations on single and double panels for the four-panel floor structure and three panels for the nine-panel floor structure. They could excite the fundamental and higher modes of vibration of the floor structures, as will be discussed in a later section of this paper.

Four pattern loading cases were used to investigate the dynamic responses of the four-panel floor system. They are referred to as Pattern Loadings PL1-1, PL2-1, PL3-1, and PL4-1. Pattern Loading PL1-1 corresponds to a single-panel excitation, whereas Pattern Loadings PL2-1, PL3-1, and PL4-1 describe the excitation of two panels. The two panels excited were selected to represent the panels in the spanning, transverse, and diagonal directions. The single panel excited can be any one of the four panels, as the configuration is symmetrical. The mode shapes obtained from the free vibration analysis of this structure were also considered in selecting the pattern loading cases. These pattern loads are capable of exciting the higher modes of vibration of this structural system in addition to the fundamental mode. Pattern Loading PL1-1 corresponds to the human activity performed on Panel 1, Pattern Loading PL2-1 corresponds to the human activity performed on Panels 1 and 3, Pattern Loading PL3-1 corresponds to the human activity performed on Panels 1 and 2, and Pattern Loading PL4-1 corresponds to the human activity on Panels 1 and 4. In addition to evaluating the response of the activity panels, it is important to evaluate that of the nonactivity panels, which may be used for various occupancy fit-outs other than dance-type activities. These fit-outs are mainly governed by the acceleration response raised by the human events in the activity panels.

Two pattern loading cases were used for the investigation of the nine-panel floor structures, and they are referred to as Pattern Loadings PL1-2 and PL2-2. Both pattern loading cases excite three panels, with Pattern Loading PL1-2 exciting the three consecutive panels along the rib-spanning direction (Panels 1, 4, and 7) and Pattern Loading PL2-2 exciting three panels at transverse locations (Panels 1, 2, and 3). These configurations can excite not only the first mode of vibration, but also the higher modes of vibration of the floor system. As discussed previously, the nonactivity panels may be used for other types of occupancies or human-induced activities that are less energetic.

RESULTS OF DYNAMIC ANALYSIS AND DISCUSSION

Free vibration response

At first, free vibration analyses of the two structural models were carried out to determine their natural frequencies and the corresponding mode shapes. Free vibration analysis of the four-panel structural model indicated that the fundamental natural frequency is approximately 4.0 Hz. Figure 7 shows the first four modes of vibration and the corresponding natural frequencies. The complex vibration modes of the multi-panel floor are evident from this figure, and the pattern loads considered herein could excite these modes. Free vibration analysis of the nine-panel floor structure model showed that the fundamental natural frequency is approximately 4.34 Hz. Figure 8 shows the first four modes of vibration and the corresponding natural frequencies. These complex vibration modes of the nine-panel floor structure can also be excited by the pattern loads considered herein.

Dynamic response

A comprehensive dynamic analysis of the two floor structures under the loads described previously was carried

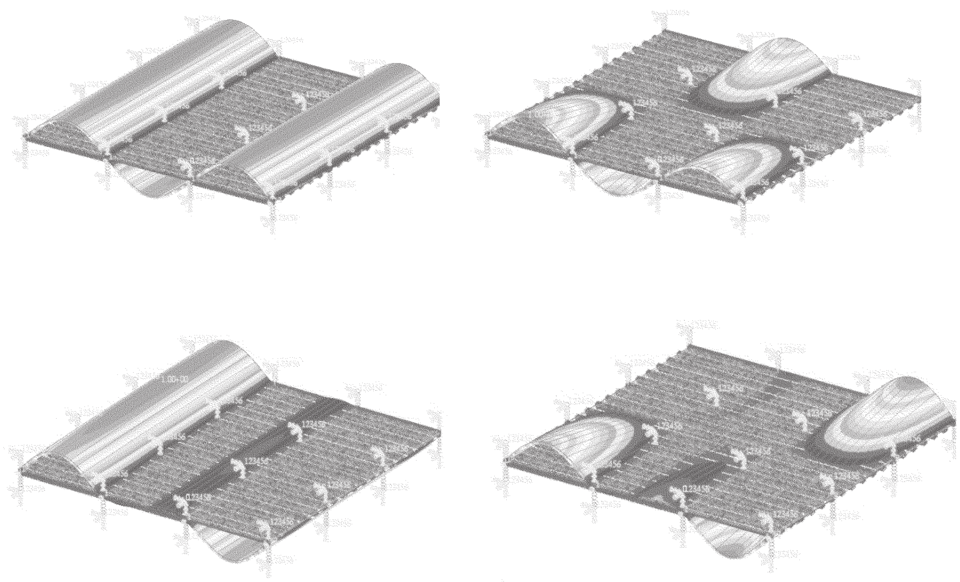


Fig. 8—Mode shapes and natural frequencies of nine-panel floor model: (a) first mode at 4.3 Hz; (b) second mode at 4.8 Hz; (c) third mode at 5.4 Hz; and (d) fourth mode at 5.9 Hz.

out, but only the results on the vibration characteristics are presented herein. For each pattern load, additional parameters of 1) live load density (two values); 2) structural damping (four values); 3) contact ratio (four values); and 4) human load frequency (ranging from 1.5 to 3.5 Hz) were considered to obtain the response of the composite floor panels under the full range of operating conditions, and hence enable a reasonable assessment of their performance. The pattern loads were applied to the FE model of the composite floor structure one at a time.

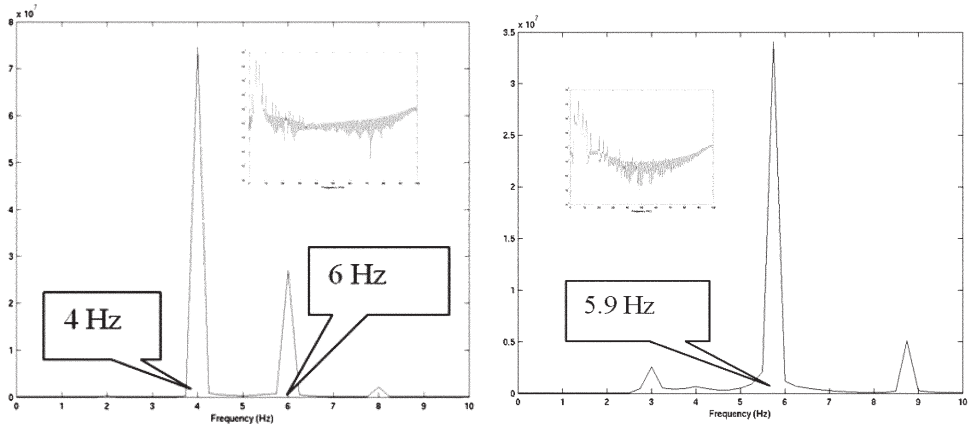
Steady-state dynamic responses at the mid-locations of each panel, which gave the maximum values of deflection and acceleration, are obtained for each of these pattern loadings across the full range of the other parameters. When there is more than one activity or nonactivity panel, the average values of the panel responses (for deflections and accelerations) are used for these panels. The dynamic amplification factor (DAF) for deflection, which is the ratio of maximum dynamic to static deflection, was calculated for each load case (that is, for each pattern loading, damping value, contact ratio, and range of load frequencies) and compared against the allowable serviceability deflection limits. These results are presented and discussed in References 18 and 19. The acceleration responses of the floor structures for each load case were compared with the human perceptibility criteria published by AISC[6] to establish the possible occupancies of the floor panels under the different operating conditions. These results are also presented and discussed in Reference 19. The response of the structural floor systems in terms of dynamic amplifications in deflections and accelerations depended on the pattern loading case and operating conditions, such as damping, load density, contact ratio, and panel of interest. The results can be used to assess the floor panels for deflection serviceability and select suitable occupancies in which the accelerations are within the limits of human perceptibility.[19]

When the DAFs were plotted against the activity frequencies for the four-panel model, there were two major peaks corresponding to activity frequencies of 2 and 2.9 Hz across all activity types and loading conditions. There was also a peak at 2.7 Hz, which was distinct only under Pattern Loading PL4-1. Under both Pattern Loadings PL1-1 and PL2-1, this peak (at 2.7 Hz) occurred for normal jumping activity (α = 0.33), but only at the lower damping levels (1.6 and 3%), and it was altogether absent under Pattern Loading PL3-1. For the nine-panel model, the peaks in the floor response (DAFs of deflections) were seen primarily at the activity frequencies of 2.1 Hz under Pattern Loading PL1-2. There were secondary peaks at activity frequencies of 1.8 and 2.7 Hz for the activities of high-impact and normal jumping (α = 0.25 and 0.33), but they were not distinct at the higher damping levels of 6.0 and 12.0%. Under Pattern Loading PL2-2, the major peaks in the response occurred at activity frequencies of 1.6 and 2.4 Hz for Pattern Loading PL2-2. There was a secondary peak at 2.1 Hz for normal jumping (α = 0.33) at lower damping levels.

VIBRATION CHARACTERISTICS UNDER PATTERN LOADS

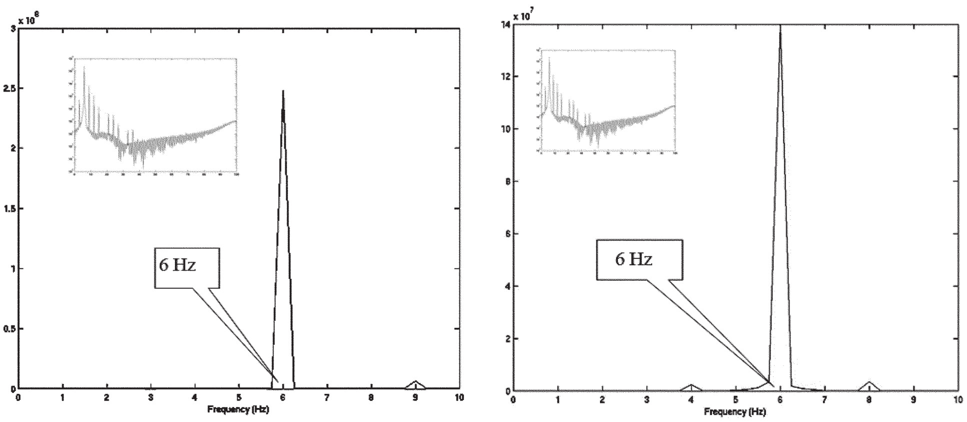
Four-panel floor structure

As discussed previously, depending on the pattern loading, the deflection responses at different contact ratios and damping levels gave maximum responses at activity frequencies of 2.0, 2.7, and 2.9 Hz. This information was used to investigate the excitation of higher and multi-modal vibration in the floor structures through Fourier amplitude spectra for the acceleration response. The Fourier amplitude response spectrum for the acceleration of the structural system under Pattern Loading PL1-1 at an activity frequency of 2 Hz, a damping level of 1.6%, and a contact ratio α = 0.25 is shown in Fig. 9(a). It can be seen that there are two distinct peaks at frequencies of 4.0 and 6.0 Hz. Figure 9(b) depicts a similar spectrum of the acceleration at an activity frequency of 2.95 Hz, in which a single peak can be found near 5.9 Hz. These peaks in the Fourier amplitude spectra are due to the excitation of different modes by the harmonics of the particular human-induced pattern loading. In this particular case, Pattern Loading PL1-1 at an activity frequency of 2 Hz causes the floor system to vibrate at the first mode



(a) (b)

Fig. 9—Fourier amplitude spectra for acceleration at activity frequency: (a) 2.0 Hz; and (b) 2.95 Hz under Pattern Loading PL1-1 (or Pattern Loading PL2-1).



(a) (b)

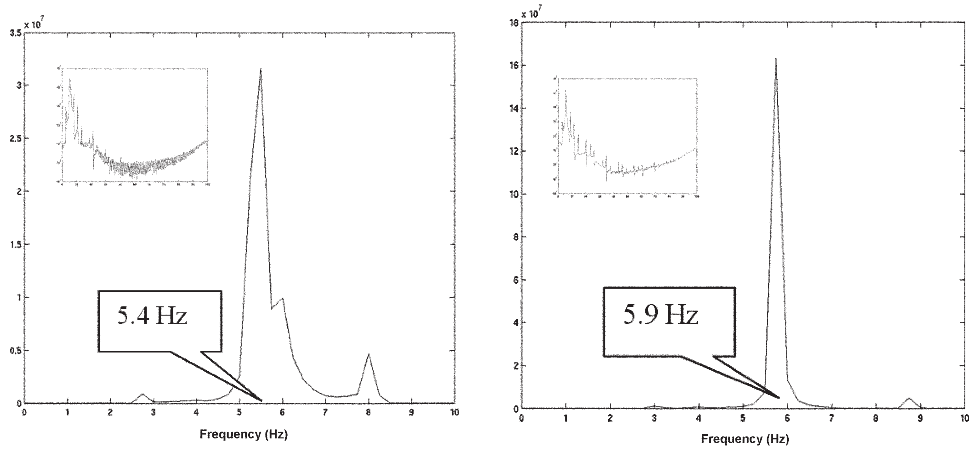
Fig. 10—Fourier amplitude spectra for acceleration at activity frequency: (a) 2.95 Hz; and (b) 2 Hz under Pattern Loading PL3-1.

of 4 Hz and the third mode of 6 Hz by the second and third harmonics, respectively, of the load frequency. Thus, the two peaks in Fig. 9(a) correspond to the excitation of the first and third modes of the floor system (refer to Fig. 7 for the mode shapes) by the second and third harmonics of the forcing frequency of 2 Hz. The single peak in Fig. 9(b) corresponds to the excitation of the third mode by the second harmonic of the forcing frequency of 2.95 Hz. Analogous results were obtained for Pattern Loading PL2-1 at the activity frequencies of 2 and 2.95 Hz, and the corresponding Fourier spectra are as shown in Fig. 9.

Similar Fourier amplitude spectra for the accelerations under Pattern Loadings PL3-1 and PL4-1 had only a single dominant peak for each activity frequency. Under Pattern Loading PL3-1, these dominant peaks were at or near 6 Hz caused under activity frequencies of 2 and 2.95 Hz. The third mode near 6 Hz was excited by both the third harmonic of the activity frequency of 2 Hz and also by the second harmonic of the activity frequency of 2.95 Hz, as seen in Fig. 10. Under Pattern Loading PL4-1, the dominant peaks occurred at frequencies of 5.4 Hz and 5.9 Hz caused by the activity frequencies of 2.7 Hz and 2.95 Hz, respectively, as shown in Fig. 11. The second mode of the floor structure at 5.4 Hz was excited by the second harmonic of the human-induced activity frequency of 2.7 Hz under Pattern Loading PL4-1, which also excited the third mode at 5.9 Hz by the second harmonic of the activity frequency of 2.95.[19] This shows that the four-panel floor system responds not only at its first mode, but also at its second and third modes—depending on the pattern loading—with the higher modes of vibration excited by the second or third harmonic of the forcing frequency. These results confirm the excitation of higher and multi-modal vibration in the floor structure and highlight the inadequacy of the current simplified procedures, which consider only the fundamental mode for the design and evaluation of floor vibration.

Nine-panel floor structure

As discussed previously, peaks in the response under Pattern Loading PL1-2 occurred primarily at the activity frequency of 2.1 Hz, whereas under Pattern Loading PL2-2, peaks in response occurred at activity frequencies of 1.6 and 2.4 Hz. Fourier amplitude spectra of acceleration responses at these frequencies were obtained to study the vibration response of the floor structure. The typical Fourier amplitude spectrum of an acceleration response of the floor under Pattern Loading PL1-2 at the activity frequency of 2.1 Hz (for $\alpha = 0.25$ and damping of 1.6%) is presented in Fig. 12.



(a) *(b)*

Fig. 11—Fourier amplitude spectra for acceleration at activity frequency: (a) 2.7 Hz; and (b) 2.95 Hz under Pattern Loading PL4-1.

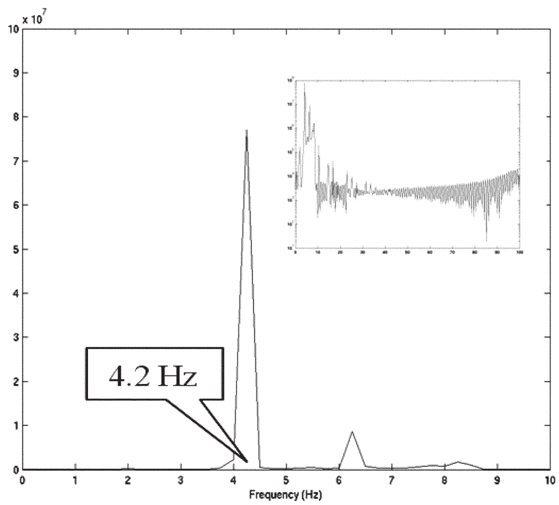


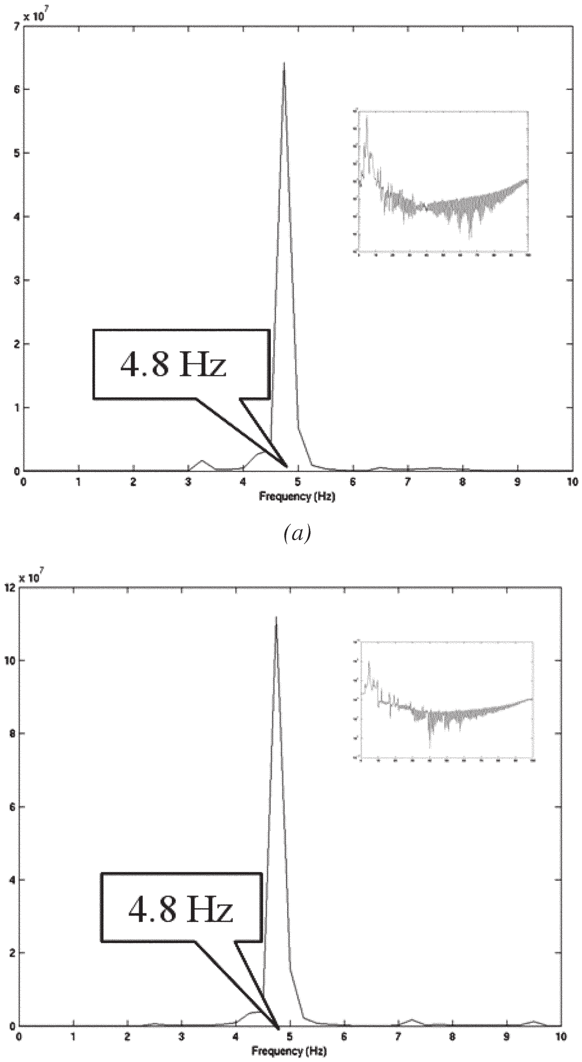
Fig. 12—Fourier amplitude spectrum for acceleration at activity frequency of 2.1 Hz under Pattern Loading PL1-2.

This Fourier amplitude spectrum has a peak at a frequency of 4.2 Hz, which related to the first natural frequency of the floor system. Consequently, it can be concluded that the floor vibrated in its first mode, excited by the second harmonic of the activity frequency of 2.1 Hz. The typical Fourier amplitude spectra of acceleration responses under Pattern Loading PL2-2 at activity frequencies of 1.6 and 2.4 Hz are depicted in Fig. 13 for a foot contact ratio $\alpha = 0.25$ and a damping of 1.6%. The peaks in the Fourier amplitude response spectra occur at 4.8 Hz under both activity frequencies of 1.6 and 2.4 Hz. The frequency of 4.8 Hz relates to the second natural frequency of the floor system. Thus, it is evident that due to Pattern Loading PL2-2, this nine-panel floor system vibrated in its second mode shape. Consequently, the second and third harmonics of the activity frequencies of 2.4 and 1.6 Hz excited the second mode of the floor system.

CONCLUSIONS

The vibration characteristics of the four- and nine-panel models of a slender concrete-steel composite floor structure under human-induced dance-type pattern loads have been studied using dynamic computer simulation techniques. The load model had a number of variable parameters, such as the foot contact ratio, load intensity, and activity frequency. A range of damping values was also considered. The deflection responses of the floor structures indicated that peak responses occurred at certain activity frequencies, irrespective of the other load parameters. The Fourier amplitude spectra for the acceleration responses of the structural models at these critical activity frequencies were obtained under the pattern loads considered in this study. These spectra had peak values of the acceleration response of the floor structure at certain frequencies, which indicated the excitation of the higher modes of vibration of the floor structure in addition to the fundamental mode. The main findings of this research are summarized as follows:

- Under pattern loading, the second and third modes of the floor structure can be excited by the higher harmonics of the activity (load) frequency.
- These types of concrete-steel composite multi-panel floor structures often exhibit higher and multi-modal vibration under pattern loads and, hence, the simplified guidance for vibration mitigation in the present codes or best-practice guides, which consider only the fundamental mode, will be inadequate.
- There is potential for an adverse dynamic response of these types of floor structures due to the excitation of the higher- and multi-modal vibration unless appropriate provisions are made for them.
- It is important to consider the entire floor and its occupancy fit-out instead of a single-floor panel, as the vibration problem in any panel may not be due to the activity in that floor panel but, rather, due to activity in a different floor panel in the same floor.
- Under normal jumping activity (with a foot contact ratio of 0.33), there were additional peaks in the response at low values of damping, but these peaks tend to smooth out at higher values of damping.
- At low levels of damping up to 6%, there is a greater possibility of the excitation of higher modes of vibration of the floor structure.
- The role of damping—usually higher than 6%—in suppressing some of the higher and multi-modal vibration in these types of structures is thus evident.
- The following brief guidance may be used for addressing vibration in these types of floors:



(a)

(b)

Fig. 13—Fourier amplitude spectra for acceleration at activity frequency: (a) 1.6 Hz; and (b) 2.4 Hz under Pattern Loading PL2-2.

  - Consider the load frequency and at least the first four natural frequencies and the mode shapes of the floor.
  - Higher harmonics of the load frequency can then be compared with the frequencies of the higher modes of the floor structure to predict which modes could be excited under credible pattern loads.
  - If the higher modes are likely to be excited, consider providing adequate (usually >6%) damping to suppress some of the higher modes of floor vibration.
  - The response of nonactivity panels needs to be considered in addition to that of the activity panel.
- The analytical techniques and methods used in this study can supplement the current limited code and best-practice provisions for mitigating the impact of human-induced vibration in slender composite floor structures.

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